

Hints of R-parity violation in B decays into $\tau\nu$

N. G. Deshpande^a, A. Menon^a

^a*Institute of Theoretical Science, University of Oregon, Eugene, OR 97403*

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Abstract

In this article we show that the recently observed enhanced semi-leptonic and leptonic decay rates of the B meson into $\tau\nu$ modes can be explained within the frame work of R-parity violating (RPV) MSSM. In particular, RPV contributions involving the exchange of right-handed down-type squarks give a universal contribution to the $B^+ \rightarrow \tau\nu$, $B \rightarrow D\tau\nu$ and the $B \rightarrow D^*\tau\nu$ decays. We find that the masses and couplings that explain the enhanced B decay rates are phenomenologically viable and the squarks can possibly be observed at the LHC.

1 Introduction

The Babar collaboration [1] has reported recently improved measurements of the ratios of the semileptonic decays of $\frac{\mathcal{BR}(B \rightarrow D\tau\nu)}{\mathcal{BR}(B \rightarrow Dl\nu)}$ and $\frac{\mathcal{BR}(B \rightarrow D^*\tau\nu)}{\mathcal{BR}(B \rightarrow D^*l\nu)}$. Both these observation exceed the Standard Model (SM) expectations by more than 2σ . Furthermore, the Babar collaboration [2] also finds the branching ratio $B \rightarrow \tau\nu$ exceeds the SM prediction obtained using the global fit of the CKM matrix. We summarize the experimental measurements:

$$R^{\text{exp}}(D) = \frac{\mathcal{BR}(B \rightarrow D\tau\nu)}{\mathcal{BR}(B \rightarrow Dl\nu)} = 0.440 \pm 0.072 \quad (1)$$

$$R^{\text{exp}}(D^*) = \frac{\mathcal{BR}(B \rightarrow D^*\tau\nu)}{\mathcal{BR}(B \rightarrow D^*l\nu)} = 0.332 \pm 0.030 \quad (2)$$

$$\mathcal{BR}(B \rightarrow \tau\nu) = (1.67 \pm 0.3) \times 10^{-4}. \quad (3)$$

where for $B \rightarrow \tau\nu$ we used the HFAG average value [3]. For comparison the expected SM values are [4, 5]:

$$R^{\text{SM}}(D) = 0.297 \pm 0.017 \quad (4)$$

$$R^{\text{SM}}(D^*) = 0.252 \pm 0.003 \quad (5)$$

and we take the more conservative prediction based on the average $|V_{ub}|$ given in Ref. [6] for

$$\mathcal{BR}(B \rightarrow \tau\nu)^{\text{SM}} = (1.04 \pm 0.31) \times 10^{-4} \quad (6)$$

We therefore find that each of these rates are enhanced over the Standard Model expectation. Clearly if these deviations from the SM are taken seriously there has to be new physics involved which distinguishes the τ -lepton from the lighter lepton families, μ and e . We also know from decays of the Z and W gauge bosons that universality of leptons is obeyed to a high degree of precision in those decays. Thus exchange of new particles that preferentially couple to the third family are probably necessary.

Many theoretical attempts have been made recently to understand the above discrepancies. Purely phenomenological studies based on four fermion operators have been carried out in Ref. [7, 8, 9]. Specific models involving extra Higgs doublets [10] and leptoquarks [8] have been discussed.

In this note we consider a model involving R-parity violating interactions in the superpotential previously studied in Ref. [11, 12]. In particular, down-type squark, \tilde{d} , exchange provides a mechanism to explain all the data reasonably well. This model has the further virtue of providing a universal explanation for all the enhancements in the processes involving the transition $b \rightarrow (c, u)\tau\nu$.

2 R-parity violating MSSM

In this section we will give a brief overview of the R-parity violating (RPV) MSSM and discuss the possibility that it can explain the enhanced decay rates of the B meson. We will also briefly discuss the possibility of observing this scenario at the LHC.

2.1 Setup

Once we allow for R-parity violating operators, the down-type Higgs chiral superfield H_d and the three lepton superfields L_i cannot be distinguished. Hence the minimal R-parity violating superpotential terms allowed by $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance are [13, 14]

$$W_{\text{RPV}} = \mu_i L_i H_u + \frac{1}{2} \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2} \lambda''_{ijk} U_i D_j D_k \quad (7)$$

Chiral Field	Q	U	D	L	E	H_u
Z_3^B charge	0	-1	1	-1	-1	1

Table 1: Z_3^B charge assignments of the MSSM particle content

where the generation indices $(i, j, k) \in (1, 2, 3)$ for the Q, U, D, E superfields and $(i, j) = (1, 2, 3, 4)$ for L superfield. $SU(2)_L$ and $SU(3)_C$ gauge invariance implies $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda''_{ijk} = -\lambda''_{ikj}$. In addition to these superpotential RPV operators, R-parity violating soft-supersymmetry breaking operators are also present. As we will be working at low $\tan \beta$ these operators give sub-dominant contributions to the semi-leptonic decays of the b -quark and are not of interest in this article.

The strong constraints from proton decay can be avoided by imposing the discrete Z_3^B baryon number symmetry discussed in Ref. [15]. The charge assignments for each of the MSSM chiral superfields are shown in Tab. 1 where a chiral superfield Φ transforms as $\Phi \rightarrow \Phi e^{2\pi i \phi / N}$ for Z_3^B charge ϕ . The Z_3^B symmetry explicitly excludes the λ'' proportional terms. Furthermore in order to avoid experimental and cosmological constraints on neutrino mass we assume that both the bilinear RPV term μ_i and the related soft-SUSY breaking term are small and hence their phenomenological impact on b -decays are negligible. Therefore under these simplifying assumptions and rotating in to the basis of the physical H_d the total superpotential has the form

$$W = W_{\text{MSSM}} + W_{\text{RPV}} \quad (8)$$

$$W_{\text{RPV}} = \frac{1}{2} \hat{\lambda}_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \hat{\lambda}'_{ijk} \hat{E}_i \hat{Q}_j \hat{D}_k^c \quad (9)$$

Now rotating into the mass eigenbasis of the charged leptons and the quarks we find

$$W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} (N_i E_j - E_i N_j) E_k^c + \lambda'_{ijk} (N_i D_j - V_{jl}^{\text{CKM}} E_i U_l) D_k^c \quad (10)$$

where the un-hatted λ and λ' are the effective RPV couplings in this basis.¹ To avoid flavor constraints (see references in [13]) involving the first two generations of quarks we can assume a Froggatt-Nielsen like mechanism [16] for generating the heirarchy $\lambda'_{33k} \gg \lambda'_{ijk}$ for all $i, j \neq 3$.

2.2 RPV contributions to B rare decays

Using Eq. (10) the RPV fermion-fermion-sfermion interaction terms are

$$\begin{aligned} \mathcal{L}_{\text{RPV}} \subset & -\lambda'_{ijk} \left(\tilde{\nu}_{iL} \bar{d}_{kR} d_{jL} + \tilde{d}_{jL} \bar{d}_{kR} \nu_{iL} + \tilde{d}_{kR}^* \bar{\nu}_{iR}^c d_{jL} - V_{jl}^{\text{CKM}} \left(\tilde{l}_{iL} \bar{d}_{kR} u_{lL} + \tilde{u}_{lL} \bar{d}_{kR} l_{iL} + \tilde{d}_{kR}^* \bar{l}_{iR}^c u_{lL} \right) \right) \\ & - \frac{1}{2} \lambda_{ijk} \left(\tilde{\nu}_{iL} \bar{l}_{kR} l_{jL} + \tilde{l}_{jL} \bar{l}_{kR} \nu_{iL} + \tilde{l}_{kR}^* \bar{\nu}_{iR}^c l_{jL} - (i \leftrightarrow j) \right) + \text{h.c.} \end{aligned} \quad (11)$$

Hence the two possible contributions to the semi-leptonic decays of the B meson are due to the exchange of sleptons and down-type squarks shown in Fig. 2.2. Integrating out the sleptons and squarks we find

¹We have chosen to leave the neutrinos in the gauge basis as the final state neutrino in the operator expansion is also in the gauge basis.

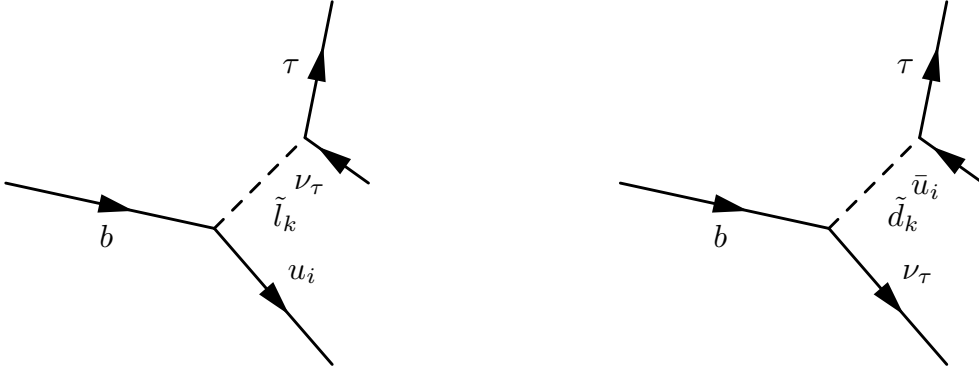


Figure 1: Squark and slepton induced rare b-quark decays

the 4-fermi interaction terms and keeping only the leading λ and λ' terms

$$\begin{aligned} \mathcal{L}_{4f} \subset -V_{sm}^{\text{CKM}} & \left[\lambda_{ijk} \lambda'_{rst} \left(\frac{V_{jl}^L V_{rl}^{*L}}{m_{\tilde{l}_i}^2} \right) (\bar{l}_k P_L \nu_i) (\bar{u}_m P_L d_t) + \right. \\ & \lambda_{ijk} \lambda'_{rst} \left(\frac{V_{(k+3)l}^{*L} V_{rl}^L}{m_{\tilde{l}_i}^2} \right) (\bar{\nu}_i C P_L l_j) (\bar{d}_t P_L u_m) + \\ & \lambda'_{ijk} \lambda'_{rst} \left(\frac{V_{jl}^D V_{(t+3)l}^{*D}}{m_{\tilde{d}_i}^2} \right) (\bar{\nu}_i C P_L l_r) (\bar{d}_k P_L u_m) + \\ & \left. \lambda'_{ijk} \lambda'_{rst} \left(\frac{V_{(k+3)l}^D V_{(t+3)l}^{*D}}{m_{\tilde{d}_i}^2} \right) (\bar{l}_r \gamma^\mu P_L \nu_i) (\bar{u}_m \gamma_\mu P_L d_j) \right] \end{aligned} \quad (12)$$

where C is the charge conjugation operator, P_L is the left projection operator, V^D is down-squark rotation matrix and V^L is the slepton rotation matrix. The second coefficient disappears for each of the processes we are considering due to the antisymmetric nature of λ_{ijk} . Furthermore in the limit when the left-right mixing elements in the slepton and down-squark mass matrices are small, the diagonalization matrices V^D and V^L are the identity. Hence the 4-fermi interaction terms reduce to

$$\mathcal{L}_{4f} \subset -V_{3m}^{\text{CKM}} \left[\frac{\lambda_{3j3} \lambda'_{j33}}{m_{\tilde{l}_j}^2} (\bar{\tau} P_L \nu_\tau) (\bar{u}_m P_L b) + \frac{|\lambda'_{33k}|^2}{m_{\tilde{d}_k}^2} (\bar{\tau} \gamma^\mu P_L \nu_\tau) (\bar{u}_m \gamma_\mu P_L b) \right] + \text{h.c.} \quad (13)$$

where we have imposed the hierarchy $\lambda'_{33k} \gg \lambda'_{ijk}$ for all $i, j \neq 3$ and we have only kept the leading terms in λ' . We note that the first term has exactly the same form as the operator induced by the charged Higgs exchange in the MSSM and the second term has an identical structure to the Standard Model. A combined analysis of the contributions from both R-parity violating terms and the charged Higgs terms have previously been studied in Ref. [17, 18]. However we shall assume the charged Higgs mass m_{H^\pm} is large and therefore the charged Higgs contribution can be neglected. Notice that the slepton contribution is suppressed compared to the squark contribution due to the $\lambda'_{33k} \gg \lambda'_{j33}$ because $j \neq 3$ for non-vanishing λ . Furthermore as the slepton is purely left-handed, if its contribution to $B \rightarrow \tau \nu$ interferes constructively with the Standard Model, then its contribution to $R(D)$ must necessarily be destructive. Therefore it is difficult for slepton contribution to simultaneously explain the increase in $B \rightarrow \tau \nu$, $R(D)$ and $R(D^*)$ [10]. The second term enhances all the three B decay modes by a universal constant

$$L_{\text{EFF}} = -V_{3m}^{\text{CKM}} \frac{4G_f}{\sqrt{2}} [1 + \Delta] (\bar{u}_m \gamma^\mu P_L b) (\bar{\tau} \gamma_\mu P_L \nu_\tau) \quad (14)$$

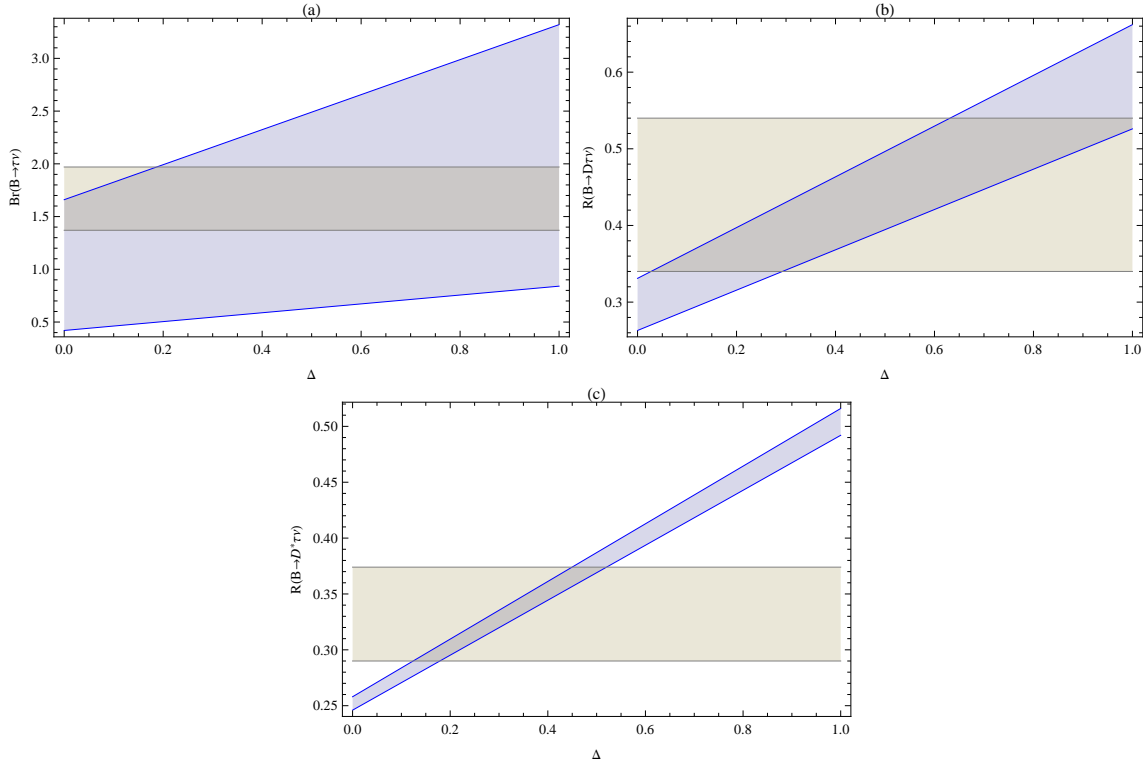


Figure 2: Dependence on Δ of the three observables: (a) $\mathcal{BR}(B^+ \rightarrow \tau \nu)$, (b) $R(D)$ and (c) $R(D^*)$. The horizontal gray band corresponds to the 2σ experimentally allowed values, while the blue band corresponds predicted values in RPV supermetric models assuming the 2σ uncertainties in the Standard Model predictions.

where

$$\Delta = \frac{\sqrt{2}}{4G_f} \frac{|\lambda'_{33k}|^2}{2m_{\tilde{d}_k}^2}. \quad (15)$$

In Fig. 2.2 we show dependence of $\mathcal{R}(B \rightarrow \tau \nu)$, $R(D)$ and $R(D^*)$ on Δ , respectively. The horizontal grey bands correspond to the 2σ experimentally allowed regions, while the blue bands correspond to the predicted values for each of these observables assuming the 2σ uncertainty in the SM calculated value. In particular we see that the $R(D^*)$ observable puts the strongest constraints on Δ and leads to the constraint that

$$0.12 \lesssim \Delta \lesssim 0.52. \quad (16)$$

Our proposal leaves the distribution of the τ -lepton and the D^* polarization the same as in the Standard Model. Observing polarization that differ from the Standard Model would be a way of distinguishing our model from other suggestions.

2.3 Observing this scenario at LHC

Assuming that the enhancement of the observables above their Standard Model values is purely due to RPV supersymmetry involving the third generation, the dominant production mechanisms for the colored SUSY particles are unmodified. However the decays of the stops, sbottoms and staus can be significantly modified. In particular, as a large λ'_{333} is needed to explain the enhanced decays of the B mesons the decays $\tilde{t} \rightarrow b l^+$ and $\tilde{b} \rightarrow b \nu$ would compete with their standard SUSY decay channels.

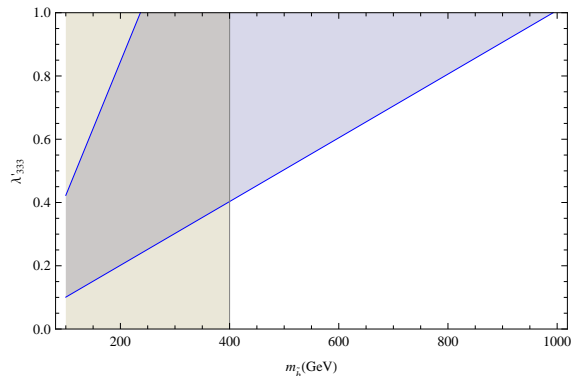


Figure 3: The blue (dark gray) region of the λ'_{333} vs. $m_{\tilde{b}_R}$ parameter space can explain the observed enhancement in B semi-leptonic and leptonic decays. The vertical grey region is excluded by the ATLAS search for sbottoms.

For stops, the $gg \rightarrow t\bar{t}^* \rightarrow b\bar{b}\tau^+\tau^-$ channel is similar to the Standard Model $gg \rightarrow t\bar{t} \rightarrow b\bar{b}\tau^+\tau^-\nu_\tau\bar{\nu}_\tau$ channel. Hence for stop masses $m_{\tilde{t}} \lesssim 200$ GeV this search mode could be quite challenging. A detailed collider study of the prospects of observing this scenario in this channel is beyond the scope of this paper.

For sbottoms, the $gg \rightarrow \tilde{b}\tilde{b}^* \rightarrow b\bar{b}\nu_\tau\bar{\nu}_\tau$ is similar to the standard SUSY search $\tilde{b} \rightarrow b\chi_0^1$ with $m_{\chi_0^1} = 0$. Hence the ATLAS limits [19] $m_{\tilde{b}} \gtrsim 400$ GeV are relevant to this study. In Fig. 2.2 we present a combination of the constraint from ATLAS on the sbottom mass and from Eq. (16) for the case where only $\lambda'_{333} \neq 0$. In Fig. 2.2 the vertical grey region is excluded by the ATLAS search, while the blue (dark grey) area is the allowed region of parameter space in the $\lambda'_{333} - m_{\tilde{b}_R}$ plane. In particular a large RPV couplings is needed in order to explain the observed enhanced decay rates of $B^+ \rightarrow \tau\nu$, $B \rightarrow D\tau\nu$ and $B \rightarrow D^{(*)}\tau\nu$. Furthermore, future searches in $b\bar{b}$ +MET channel at LHC will be able to probe a significant portion of the parameter space of this scenario.

3 Conclusions

We have proposed a model that gives a universal explanation of the experimentally observed enhancements in the leptonic and semi-leptonic decays of the B meson into the third generation of leptons. We invoke R-parity violating operators in the the MSSM. Only the operator $\lambda'_{ijk}L_iQ_jD_k$ is necessary, and the effective interaction resulting from d-squark exchange has the same form as the SM current-current interaction. We estimate the strength of the new interaction using a fit to the data, and derive bounds on the d-squark mass assuming perturbative unitarity holds for the Yukawa couplings. We then discuss briefly the production and signatures of d-squark in this model. We conclude that the model is testable at the LHC.

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